The Geological Society of America
Special Paper 486
2012

Mapping the domain of spatial thinking in the geosciences

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INTRODUCTION TO PAPERS

Expert geoscientists, like experts in other fields, are often oblivious to the sophisticated skills that they use every day. These are often skills for which they have innate talent, or with which they struggled long ago—often thinking they were the only one in the profession for whom this was a difficult task. In geoscience, spatial skills are one of the most profound examples of this effect. The following article by Lynn Liben and Sarah Titus makes a compelling case for the importance of spatial skills in geosciences, documenting both the wide variety of geoscience tasks that require spatial skills and the wide variety of spatial skills required. Liben, who has dedicated her career to studying spatial skills, and Titus, one of the new breed of geoscience faculty with research interests in both structural geology and geoscience education, bring to the paper the breadth and depth of expertise needed to make this case in detail.

Liben and Titus use a vignette describing a structural geologist in the field as a basis for connecting general spatial concepts and skills (such as mental rotation) with geospecific concepts (such as strike and dip) and skills (such as making a geologic cross section). This is a powerful approach for both clarifying the connection and describing the skills. The vignette allows geoscientists, more familiar with geoscience skills, and cognitive scientists, more familiar with general spatial skills, to work together and communicate accurately. Commentary writers Cesar Delgado, Stephen Reynolds, and Darby Dyar all make use of the vignette and its explanatory power in discussing extensions of the framework developed by Liben and Titus. Delgado, a cognitive scientist who studies students' ideas about space and time, urges us to expand the discussion of spatial concepts to include the one-dimensional concepts of scale and size. Reynolds—a field geologist, textbook author, and geoscience education researcher—describes the important roles that disembedding (the visual selection and grouping of geologically salient features) and visual-penetrative ability (mentally constructing the interior of an object) play in the geosciences. Dyar, a mineralogist, petrologist, and the author of a mineralogy text, argues for the importance of the type of visualization skill that supports the identification of objects, and discusses the relative importance of spatial versus object visualization in the various subdisciplines of geosciences.

Karl Grossner, a geographer, describes the importance of collaborations among scientists, cognitive scientists, and education specialists in defining the relationship between spatial skills and expertise in various disciplines. In this comparison, geosciences makes an interesting case study and rich arena for study because spatial skills are so central to so many aspects of geosciences. High-spatial geoscientists working at the most spatially demanding of geoscience tasks push the boundaries of what humans are capable of spatially. However, as Nora Newcombe notes, demonstrating that spatial skill causes success in geosciences, or that the lack thereof causes failure, is work that still needs to be done. As with any case study, part of its power lies in comparison to other cases. Grossner takes us down that path, describing early work to identify, characterize, and compare spatial skills across a range of disciplines. As he notes, this will be a powerful approach for future research, yielding insight into the specific cases and identifying important generalities.

A primary reason for studying spatial skills in science, technology, engineering, and math (STEM) is to obtain insights that will assist in developing needed experts for the future. Newcombe describes how knowledge of the relationship between spatial skills and geoscience expertise can be used to enhance geoscience education by either (1) improving students' facility with needed spatial skills or (2) reducing the degree to which learning depends on prior development of spatial skills. She organizes the recommendations put forward by Liben and Titus into this framework. Dyar's commentary on the relationships among spatial

Manduca, C.A., and Kastens, K.A., 2012, Mapping the domain of spatial thinking in the geosciences, *in* Kastens, K.A., and Manduca, C.A., eds., Earth and Mind II: A Synthesis of Research on Thinking and Learning in the Geosciences: Geological Society of America Special Paper 486, p. 45–49, doi:10.1130/2012.2486(09).

skill, gender, and choice of geoscience subdiscipline shows the importance of effective spatial education in fostering a diverse set of experts. As understanding of the specific spatial skills required in different geoscience subfields matures, geoscience education can be more targeted in supporting development of needed skills. Meanwhile, experts in many fields of geosciences are exploring new visualizations enabled by modern computer power, with the goal of enhancing their own ability to perceive spatial patterns and infer causal processes behind those patterns. How best to use such visualizations to improve nonexperts' learning remains an open question.

As a set, the Liben and Titus paper and associated commentaries address the important interaction between expertise and experiment in developing teaching methods. Reynolds articulates the lessons he has learned from experience in the field and experience in the classroom and urges geoscience faculty to reflect on these experiences for insight into effective teaching. Indeed, there is substantial wisdom in teaching methods that have evolved through time, producing generations of geoscientists. However, as Dyar points out, we may not be serving all students equally well with these methods. Research on cognition and in education will help us to identify principles that refine our pedagogy, improve our ability to recognize students with different spatial ability, and implement learning strategies that capitalize on their strengths and assist them past their weaknesses.

GUIDE TO THE CONCEPT MAP

The intellectual landscape of spatial skills, the ways in which they are used by geoscientists, and the methods we use to help students learn highly spatial geoscience concepts and skills, is vast and complicated (National Research Council, 2006). Figure 1 begins to map this terrain, with five main branches: spatial concepts, spatial representations, spatial skills, pedagogical approaches, and individual & group differences.

Humans employ a huge suite of spatial concepts. Those that feature prominently in geosciences include distance, gradient, trajectory, speed, orientation, scale, size, and symmetry (for others, see Grossner, this volume, his Table 1). Geoscience students need to learn to describe Earth phenomena in terms of these spatial concepts. In addition, they must learn to develop causal hypotheses that align with available spatial constraints. The geologist featured in the vignette by Liben and Titus demonstrates such reasoning when she infers that the igneous rocks most likely intruded previously deposited sandstone because of subtle aspects of the orientation of the layers in the sandstone and the crystals in the igneous rock.

Geoscientists use a large number and variety of spatial representations (Kastens and Manduca, this volume). Some of these are specific to geosciences (or at least typically first encountered by students in geoscience courses, e.g., stereoplots), while others are adapted from broader uses (e.g., maps, graphs, and time lines). The concept map distinguishes among 1-D, 2-D, 3-D, and 4-D (with time) representations (see also Kastens and Manduca, this volume, their figure 1). Liben and Titus' vignette geologist uses two-dimensional representations extensively, in planning her day's work, in recording her observations, and in presenting her results for publication. Delgado calls our attention to the importance and nontriviality of one-dimensional concepts of size and scale. Three-dimensional representations include physical models, such as the Sun-Moon-Earth model used by Taber (this volume). The "zero-dimensional" node depicts what are sometimes called "spatializations" (Skupin, 2007), i.e., visualizations in which the dimensions of the representation convey nonspatial attributes of the system being represented, with the intent of leveraging the viewer's perceptual and cognitive abilities to better understand complex data and underlying causal processes. Examples include the physical oceanographers' temperature-salinity diagrams for depicting water masses, and the petrologists' phase diagrams (e.g., Dutrow, 2007), in which the dimensions may depict temperature, pressure, or composition. Educators confront a complex chicken-and-egg relationship between spatial representations and associated geoscience content. It is necessary to understand something of the content to make any sense of the representation, and yet the representation is often the means that geoscientists use to communicate about the content. For such cases, an iterative or spiraling approach to teaching the content and representational competence in parallel may be effective.

The spatial skills branch of the concept map contains some prominent visualization and spatial reasoning processes that geoscience experts use and geoscience students must master. Reynolds (this volume) calls attention to disembedding and visual penetrative ability. Disembedding in geosciences involves observing a complex scene (whether an outcrop, landscape, or data visualization), observing and recognizing patterns, and isolating the important aspects ("the signal") from distracting, nonessential ones ("the noise"). Visual penetrative ability, first described by Kali and Orion (1996) and prominent in Liben and Titus (this volume), involves envisioning the three-dimensional geometry of structures *inside* a volume using mostly two-dimensional clues from the edges of the volume. Although usually thought of in terms of a rock volume seen in an outcrop, oceanographers face a similar spatial challenge in visualizing attributes of a body of water from data gathered at the sea surface and along vertical transects. Perspective taking (Kozhevnikov et al., 2006) requires envisioning how something would appear from different vantage points, as in envisioning the phase of the Moon as seen from Earth during different configurations of the Earth-Moon-Sun system. Mental rotation is perhaps the most studied of spatial skills, going back to Shepard and Metzler (1971), and it plays a role in geosciences, as, for example, in recognizing fossils regardless of their orientation. Mental animation (Hegarty, 1992) involves developing a plausible scenario of a sequence of events based on static information, as when Liben and Titus' vignette geologist developed the scenario by which horizontal sedimentary layers could have been deformed into the current shape of Black Mesa (Liben and Titus, this volume, their figure 5). Object location memory

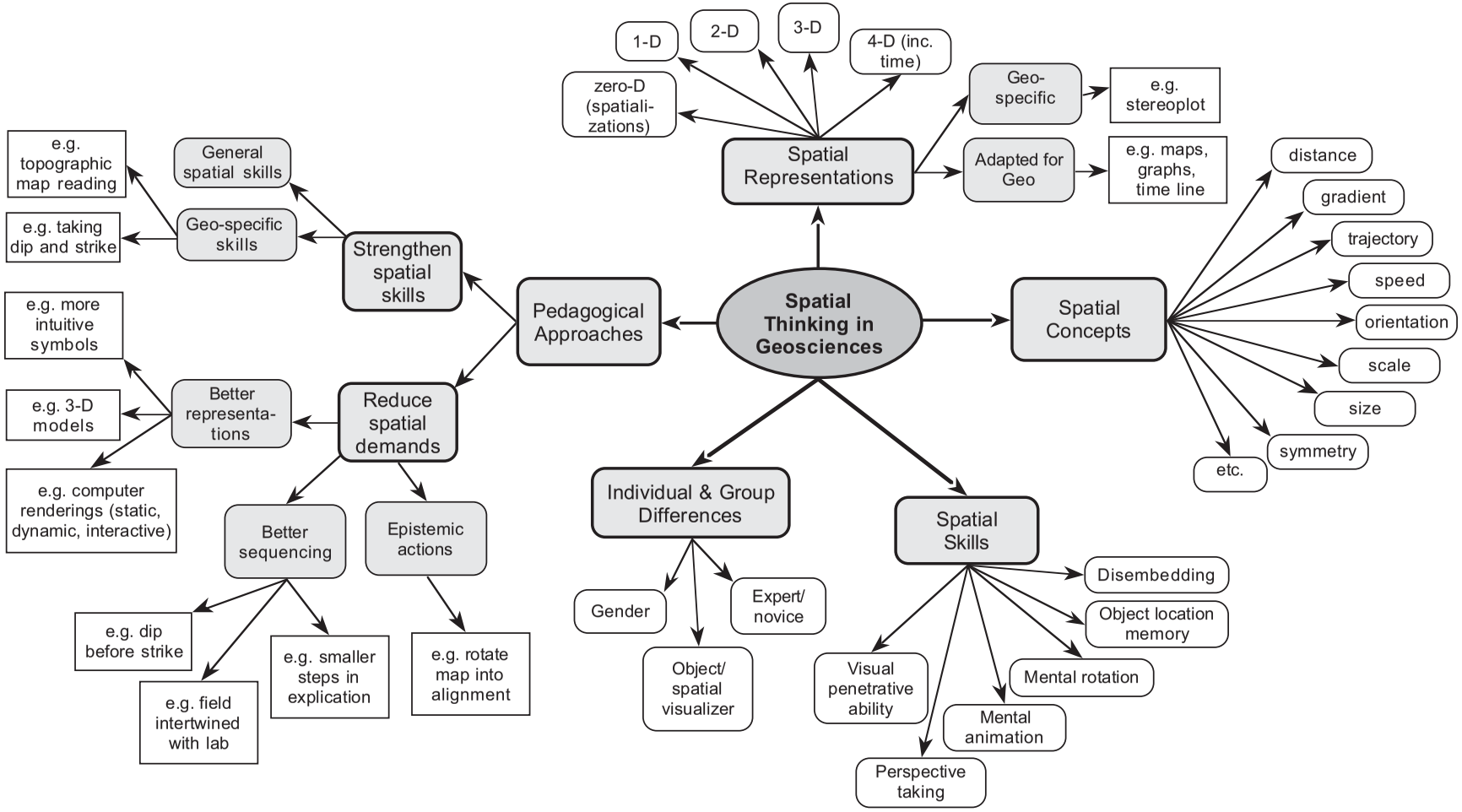

Figure 1. Concept map of spatial thinking in geosciences. Nodes in the concept map are keyed to the text by Helvetica font.

(McBurney et al., 1997) means remembering the spatial location of previously seen objects or phenomena, a valuable skill for field scientists trying to recall where they have seen features similar to those in the outcrop at hand. In light of Dyar's commentary on the differing representation of women in different subdisciplines of geosciences, it is interesting to note that this is one spatial skill on which females have been shown to outperform males.

Newcombe (this volume) inspires the subdivision of the pedagogical approaches portion of the concept map into techniques that seek to strengthen spatial skills and techniques that seek to reduce spatial demands on the student. A thorough education should do both, but different audiences or contexts may call for different emphases, such as more emphasis on reducing spatial demands for an audience of policy students and more emphasis on strengthening spatial skills for geoscience majors.

Within the branch of strengthening spatial skills, instructors and researchers can attend to either strengthening general spatial skills, such as mental rotation or perspective taking, or strengthening geospecific skills. As Newcombe (this volume) points out, it has not been demonstrated that improving general spatial skills transfers into improved performance in geosciences, so this node of the concept map should be viewed as a promising hypothesis. The evidence is stronger for discrete geospecific tasks, such as Titus and Horsman's (2009) work on structural geology tasks and Reynolds et al.'s (2006) work on topographic map interpretation, both showing improved student performance with instruction and practice. There are many spatially demanding geoscience tasks for which there is, as yet, no educational research.

Reducing spatial demands can be controversial because some instructors view this approach as shortchanging students, who could move onto the next course weak in essential geoscientists' skills. Resolution of this issue requires careful attention to learning goals: Is the goal for the student to understand earth processes or to master the techniques that geoscientists use to study Earth, e.g., to understand how landforms form or to read topographic contour maps? Even if the goal is mastery of geoscientists' skill set, reducing spatial demand may be a useful intermediate pedagogical approach. Three approaches are mapped for reducing spatial demands: Better representations (such as three-dimensional models or maps with more intuitive symbols), better sequencing of instruction (such as teaching dip before strike), and encouragement of epistemic actions. Epistemic actions (Kirsh and Maglio, 1994; Kastens et al., 2008) are physical actions that change the world in such a way as to make mental computation easier, faster, or more accurate, such as rotating a map into alignment with the represented space. All three of these suggested approaches for reducing spatial demands are ripe for further research.

Nestled in between spatial skills and pedagogical approaches, the concept map has a node for individual & group differences, referring to differences in performance on the same task between individuals or between groups. Although this node could have appeared on any of the concept maps, individual and group differences have been more of a focus of study in spatial thinking than in the other domains discussed in this volume, with literature on gender differences (e.g., Linn and Petersen, 1986; Liben, 2006; Dyar, this volume), expert/novice differences (e.g., Jones et al., 2008), and object versus spatial visualizers (e.g., Kozhevnikov et al., 2005; Kastens, 2010), among other distinctions (Hegarty et al., 2006). In planning a research agenda around spatial thinking in geoscience education, these strong individual and group differences present confounding factors in that a given intervention could plausibly have widely differing effects on different groups.

Time and space are tightly coupled in geoscience thinking, and this concept map would benefit from linkages boring though the pages of the book to connect the spatial thinking map with the Time in Geosciences concept map in the introduction to the previous section. In using spatial representations, twenty-first-century geoscience educators and education researchers can take advantage of dynamic representations that convey four dimensions (three spatial dimensions plus time), which should therefore connect to the representation node of the time concept map. Although mapped here as a spatial concept, speed is actually a ratio between a spatial concept (distance) and a temporal concept (duration). The reason that the spatial skill of mental animation (on this map) is useful for a geoscientist is because it enables him or her to tap into reasoning processes mapped on the temporal reasoning section of the time map: reasoning based on sequence, co-occurrence, rate, and cyclicity. Time is fleeting, but space is more permanent, so the geoscientist trades time for space (Piburn et al., 2002) and uses attributes recorded in space to make inferences about processes that played out over time.

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Manuscript Accepted by the Society 7 November 2011

Printed in the USA